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13. ABSTRACT (Maximum 200 words)

The goal of the program was to characterize and quantify physical processes involved in failure of brittle materials under impact loading conditions, and to synthesize results to identify properties which determine the effectiveness of a system (material and configuration) in resisting failure. This was accomplished by developing new methodologies which integrate concepts in mechanics and materials science. Among the accomplishments are: determining the pressure-shear response of alumina powders and of soda-lime glass at very high strain rates; investigating failure waves in glasses by using pressure-shear impact; measuring the pressure-shear response of pure tungsten carbide at temperatures up to 700 degrees centigrade; developing an analytical/computational theory of fragmentation based on a cohesive zone model; developing an experimental method to characterize the fragmentation response of ceramics; measuring dynamic fragmentation characteristics for alumina and silicon nitride; developing an experimental method to study biased damage evolution and projectile deflection in penetration processes.

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Enclosure 1

Summary of Progress

Dynamic Behavior of Brittle Materials

Brown University

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Shear resistance of polycrystalline ceramics

The shearing resistance of polycrystalline alumina ceramics has been shown to be strongly affected by an intergranular glassy phase that is added as a sintering aid. In order to better understand the shearing resistance of such a glassy phase, pressure-shear plate impact experiments have been conducted on two types of soda-lime glass samples: (i) thin samples for high strain rate experiments; and (ii) thick samples for wave propagation experiments.

For (i), a thin (5 micron) layer of vapor-deposited soda-lime glass was sandwiched between two hard Hampden steel plates that remained elastic during the loading. At strain rates of 2×10^6/sec to 16×10^6/sec the shearing resistance was observed to be large (over 500 MPa) and stable for shear strains less than one-half. However, at shear strains of approximately 2 the shearing resistance fell sharply to levels of 100 MPa or less. This strong strain softening appears to be related to a mechanism in which adjacent covalent Si-O bonds switch at large shear strains causing a strong relaxation of the shear stress. The overall behavior of soda-lime glass has been modeled as involving two bond switching processes: an ionic bond switching process in which the weaker ionic bonds adjacent to modifier ions switch relatively easily in a stable manner leading to stable flow, and a covalent bond switching process in which at sufficiently large shear strains the covalently bonded network becomes so distorted that a covalent bond switching process ensues. A mathematical model incorporating these two processes has been developed and used to interpret the results of the high strain rate experiments. Simulations based on this model, using reasonable values for the physical parameters, are in good agreement with the experimental results over the full range of impact conditions studied.

For (ii), thick (4.4 mm) plates of soda-lime glass were subjected to pressure-shear impact with Hampden steel plates to investigate the effect of shear on failure waves in soda lime glass. Experiments were conducted in which either a steel flyer impacted a glass target (i.e. steel/glass impact) or vice versa (i.e. glass/steel impact). The former revealed the usual failure wave features in the rear surface velocity-time profiles for the normal component of the rear surface velocity. Namely, below a threshold impact velocity the response of the glass is elastic whereas above the threshold the spall strength behind the 'failure wave' is zero and there is evidence of a recompression wave. The new insight gained from these steel/glass impact experiments is that the transverse velocity-time profile shows a reduction in the transmitted shear stress when the impact velocity is above the threshold. The glass/steel impact experiments are perhaps the most revealing in that they show the response of the glass in the "failed region" behind the "failure wave". For impact velocities above the threshold for failure waves these experiments show a pronounced loss in shearing resistance, much like that observed in the high strain rate experiments (i). Furthermore, in spite of this loss in shearing resistance the unloading response when the longitudinal unloading wave arrives is essentially the same as for the undeformed glass until the compressive stress is reduced to a small fraction of its peak value. From these observations it appears that failure wave phenomena are closely related to loss of shearing resistance in glass. Moreover, from the unloading behavior it appears that the 'failure' or loss of longitudinal stiffness occurs not during the compressive wave but during the subsequent unloading.

Threshold conditions for dynamic fragmentation of ceramic particles

A framework of a particle-impact experiment was developed and used to study the dynamic fragmentation of brittle materials. In the experiment a small, spherical particle of a brittle material impacts against a thick hard anvil. Unlike conventional particle-impact experiments, observations and measurements are focused on dynamic failure processes in the particle, minimizing, if not completely eliminating, damage to the target during the impact. The impact process is observed using the high-speed photography. Results are presented for aluminum oxide and silicon nitride particles striking a titanium diboride anvil. The radius of the particles ranged from 0.40 mm to 3.18 mm. It is observed that above a certain threshold velocity the particle undergoes fragmentation upon impact. This threshold velocity depends on the particle material properties, and decreases with increasing particle radius. An elastodynamic finite element simulation of the particle -impact experiment was carried out. The finite element simulations showed that for these experimental conditions the stress amplitude within the particle, for a given impact velocity, is independent of the size of the particle. The size of the particle influences only the contact, and thus the duration of the stress pulse applied to the particle. The size dependence of the threshold velocity was explained by using a cohesive zone model to represent the dynamics of the failure process. Thus, the experimental results allow the dynamic cohesive strength and the dynamic toughness of the material to be determined. This experiment provides a means of studying the threshold conditions for dynamic fragmentation of brittle materials, and illustrates some of the issues involved in the application of cohesive zone models to problems involving impact and dynamic fragmentation in brittle materials.

Fragmentation of brittle solids; scaling with cohesive zone formalism

Multiple fracture processes caused by high rate of loading in brittle ceramics are classified into three categories. One is the comminution in which predominantly non-cooperative nucleation-controlled multiple fracture processes progress in a particular microstructural length scale such as the grain size and the mean distance of micro flaws, which is the mean distance between weak links. Another category is the type-I fragmentation in which cooperative nucleation-controlled multiple fracture processes produce fragments larger than the size of the microstructures of weak links. The other category is the type-II fragmentation in which cooperative crack-growth-controlled multiple fracture processes generate fragments; typical examples include crack branching, crack front evolution and crack growth governed by crack-crack interaction.

In recent work, the threshold condition for comminution was derived based on a cohesive zone model. In this model the separation process is completed before the wave generated by the separation process travels the distance of the microstructure size. For the type-I fragmentation two major concepts have been developed. One is the projection scheme of cohesive responses, which is incorporated into the mean field theory to predict the relationship between the fragment size and the applied apparent strain rate. The relationship converges to the Grady-Kipp relation at the intermediate asymptotics. The projection scheme is then used as a coarse-graining transformation for the renormalization group analysis. The effective cohesive response obtained by this analysis corresponds to the experimentally measured one.

Two ScM students are performing an experiment to detect the initiation site of failure waves in glass. A spherical steel ball makes an impact on a large block of soda-lime glass. In this situation, the maximum equivalent deviatoric stress is experienced inside the glass away from the impact face. Our previous experiments by Andrews and Kim indicate that the failure must initiate at the site of maximum Von Mises equivalent stress. High speed photography set up has been designed to take the events of failure initiation in the glass. Currently some researchers speculate that the failure wave is caused by surface irregularities. This experiment can clarify the speculation.

Micromechanisms in dynamic penetration

Detailed analytical and experimental investigation of the micromechanisms driving and governing the dynamic penetration of solid projectiles into solid targets have been carried out. The experiments are designed to ensure that the failure of the projectile is completely suppressed while the failure of the target is maximized; experimental data are collected using laser-optics, high-pressure gas gun and high-speed photography. A high-pressure gas gun capable of achieving up to 1500 m/s impact velocities was installed to increase the range of impact velocities, and a normal and shear stress gradient was constructed to investigate the role of pre-stress in penetration. For brittle penetration, Molybdenum-Tungsten Alloy Steel rods are penetrated into soda-lime glass and Zerodur targets; for ductile penetration, Molybdenum-Tungsten Alloy Steel rods are penetrated into Aluminum (6061-T6) and PMMA targets.

The role of projectile length to projectile diameter ratio is also explored by varying the cross-sectional area of the projectiles. The time-dependent measurements of the size of the failure zone and the corresponding depth of penetration are obtained over a wide range of impact velocities. For brittle penetration, the time-dependent measurements of the displacement of the ejected target material jet are also obtained; while the final target crater parameters (size and profile) are also measured for ductile penetration. Choking of the ejected material jet is observed at higher penetration velocities as a transition from a normal material ejection to angular material ejection and the observed angles of ejection are measured. A partitioning of the failure zone is also observed from the experiments. For brittle targets, the failure zone is observed to be partitioned into a comminuted granular flow zone within the vicinity of the projectile and a Mohr-Coulomb plastic flow zone around the comminuted zone.

For ductile penetration, the failure zone is observed to be partitioned into a hydrodynamic zone within the vicinity of the projectile and a plastic zone around the hydrodynamic zone. For ductile penetration, a combined transient analytical theory is developed based on a phenomenological criterion involving the combinations of the work done by the projectile during the hydrodynamic flow of the liquefied target material and the plastic flow of the surrounding plastic target material. The theory takes account of the evolution, the stability and the collapse of a viscous hydrodynamic zone of finite size. The theory also takes into account the creation and the subsequent collapse of the vapor cavity within the immediate vicinity of the projectile, and the role this plays on setting the final target crater parameters. The theory is shown to predict a correct qualitative picture when compared with the experimental results, and to introduce additional important parameters to the well-known Alekseevskii-Tate hydrodynamic penetration algorithms.

For brittle penetration, a combined transient analytical theory is developed based on a phenomenological criterion involving the combinations of the work done by the projectile during the granular flow of the comminuted target material and the Mohr-Coulomb plastic flow of the surrounding target material. The granular flow is modeled using gas dynamics in order to incorporate aspects of material compressibility. The theory takes account of the evolution of a comminuted zone of finite size. A formation of an oblique shock-front within the comminuted zone ahead of the projectile is used to explain and to predict the choking of the ejected material jet. The theory is also compared to existing cavity expansion theories for brittle penetration.

Simulation of fragmentation

In our study of the basic processes of fragmentation of a brittle material reported previously, a high density of potential fracture sites was distributed throughout an elastic-brittle solid. The model is based on the finite element method, so the potential fracture sites are represented as cohesive zones at element boundaries. The material was then subjected to a very high strain rate loading, and the resulting distribution of fragments was determined by a direct numerical solution of the problem. Material parameters typical of polycrystalline ceramics were

chosen. It was found that the mean fragment size predicted by the calculations was roughly an order of magnitude last than the prediction of this same quantity obtained from the commonly used energy balance models. The main reason for this difference, we believe, is that the energy balance models overlook the transient nature of the process. Essentially, the process involves a competition in which stress tends to increase due to the imposed strain rate (at fixed stiffness) while it tends to decrease due to damage accumulation (decreasing stiffness at fixed strain). The eventual nature of final fragmentation is determined by the details of this competition process.

In the past year, a new aspect of this process which has been studied is the role of flaw strength distribution on the process. In this computational study, flaws with a range of strengths similar to a Weibull distribution were distributed throughout the elastic-brittle solid. The results of the calculations were relatively insensitive to the various random flaw distributions examined, except on the rare occasion when two or more of the weakest flaws appeared in close proximity. Another issue which emerged is the inadequacy of fragment of size as a characterization of material damage. Eventually, we moved to a description of damage based on total crack area created, no matter whether a particular crack participated in forming a separate fragment or not.

Finally, the same damage concept was applied in a study of dynamic crack propagation in a brittle-elastic material. Recent experiments reported by Sharon and Fineberg (Physical Review B, 1996) suggested that the dramatic increase in dynamic fracture toughness observed during fast crack growth in brittle materials (PMMA in their experiments) is due to the surface area created during the many unsuccessful attempts by the main crack to branch. Because this idea was consistent with our characterization of damage in materials, the experiments were simulated numerically for a material with a distribution of potential microcrack sites. In the simulations, the main crack was found to generate extensive damage in the material adjacent to the crack path. Furthermore, because all energies could be monitored continuously during the calculation, it was readily confirmed that the damage accumulation could account for the observed increase in apparent fracture toughness at high crack speed.

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